

“The Seasonal Evolution of Sea Ice Floe Size Distribution”

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LONG-TERM GOALS

This work was motivated by the desire to improve the understanding of processes governing the evolution of the marginal ice zone that forms seasonally in the southern Beaufort and Chukchi Seas region.

OBJECTIVES

The objective of this work was to determine the seasonal evolution of the floe size distribution (Figure 1), paying particular attention to the role of winter preconditioning of the ice on summer floe breakup. To achieve this objective we planned to:

1. Develop a mathematical framework for the floe size distribution.
2. Calculate the evolution of floe size distribution during spring and summer.
3. Determine the floe breaking function by tracking individual floes using high resolution imagery.
4. Estimate lateral melt rates from high resolution imagery.
5. Investigate the roles of wave action and ice preconditioning in floe breakup.
6. Assess the relative contributions of dynamics and thermodynamics to changes in the floe size distribution

APPROACH

We investigated the evolution of the floe size distribution by acquiring and using a library of high resolution images following the same groups of floes from early spring through late summer. The images were collected as part of the ONR MIZ DRI, and included images from the MEDEA/National Security and Climate Change Research Program and the Center for Southeastern Tropical Advanced Remote Sensing (CSTARS). The high resolution imagery allowed us to follow flaws formed in winter and spring and assess their impact on the summer breakup of the ice cover. Complementary large-scale, lower resolution imagery from MODIS and other platforms was also analyzed to determine changes in floe size distribution.

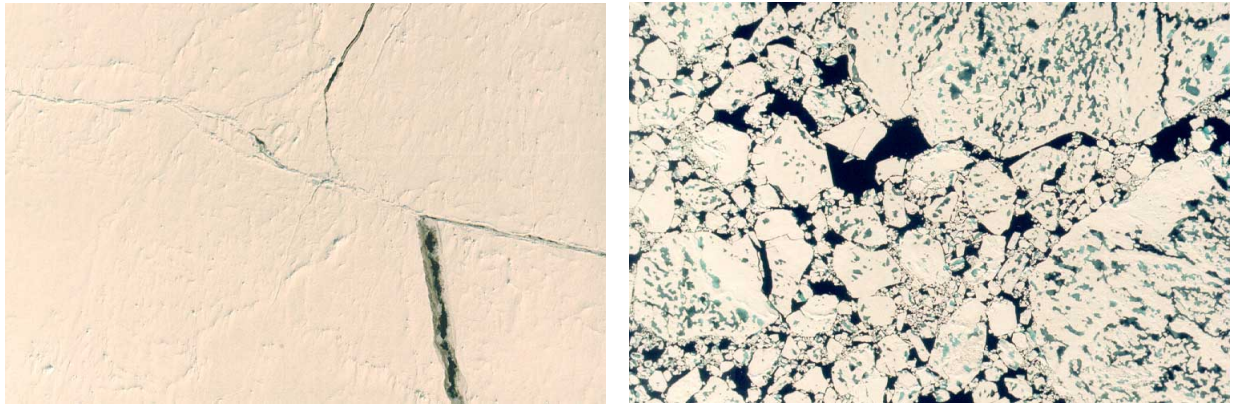


Figure 1. Aerial photographs illustrating the of the profound changes that occur in the appearance and morphology of the Arctic sea ice cover over and annual cycle. These photos were taken over the pack ice near SHEBA in May (left) and August (right) taken at an altitude of 1800 m. The scale is the same in both images.

After obtaining the imagery we used image processing software to partition the high resolution images into ice and ocean. The next step was to compute floe parameters including area, perimeter, and shape factor from the partitioned images. Individual floes were tracked to investigate how floes break. A central focus was to examine the impact of preconditioning of the floes during winter and spring to the breakup observed in summer. This information contributed to our efforts to determining the breaking function and to assess the role of wave action in breakup. Key issues concerning breakup include; what floes are likely to break, when do they break, and what causes them to break. The results can also be applied along with estimates of solar heat input to the ice – ocean system were to determine lateral melt rates. Our ultimate goal is to determine a time dependent floe size distribution governed by lateral melting and a breaking function.

WORK COMPLETED

Now in the 3rd and final year of this project and with significant involvement from the graduate student funded by the project, we have:

- (1) Published a *Journal of Geophysical Research - Ocean* article which uses the aerial photography from the Surface Heat Budget of the Arctic Ocean (SHEBA) field campaign to develop a mathematical framework for the evolution of floe size distribution (Perovich and Jones, 2014).
- (2) Obtained additional high resolution visible imagery from the MEDEA/National Security Climate Change Research Program and SAR imagery from the Center for Southeastern Tropical Advanced Remote Sensing (CSTARS).
- (3) Presented the poster “Satellite and in situ observations of Arctic sea ice floe breakup and melt” at 2013 Fall AGU
- (4) Created a library of images tracking a cluster of drifting ice-based buoys located in the southern Beaufort Sea during summer 2013 using the imagery from (2), .
- (5) Developed an image processing technique to analyze floe size distribution during the summer melt season using (4). The technique allows for the direct observation of lateral melt and the

calculation of changes in floe perimeter, and the ability to track the detailed evolution of flaw formation.

- (6) Outlined a plan to use the results of (5) to evaluate the utility of the discrete element method (DEM) in (a) advancing the understanding of the dynamic and thermodynamic processes governing the seasonal evolution of the marginal ice zone (MIZ) and (b) forecasting conditions in the MIZ in support of an anticipated increase in operational requirements.
- (7) Published a *Geophysical Research Letters* article highlighting insights gained from the analysis of high resolution imagery on the processes governing the seasonal evolution of the floe size distribution and the utility of the DEM (Arntsen et al, 2015).

RESULTS

During the SHEBA field experiment, Perovich et al. [2001] observed that the summer evolution of ice floes is a combination of winter dynamics and summer thermodynamics. Interestingly, floe breakup occurs during summer when the dynamic forcing and the internal ice stress are small. The large floes of spring are riddled with cracks and leads that form and freeze over during fall, winter, and spring. These features preferentially melt open during summer, weakening the ice so that modest divergence of the ice cover can break apart the large floes into many fragments. Associated with this breakup is an increase in the number of floes, a decrease in the size of floes, an increase in floe perimeter, and an increase in the area of open water.



Figure 2. Frozen cracks in April (left) and in July (right). Refrozen cracks formed during winter dynamics events melt quickly in summer.

Using a time series of aerial photographs from the SHEBA field experiment, Perovich and Jones (2014) quantified the seasonal floe evolution and confirmed that changes in the floe size distribution are due to a combination of thermodynamic and dynamic processes. They assumed the floe size cumulative distribution could be represented by a power law $D^{-\alpha}$, where D is the floe diameter. As summer progressed, there was an increase in α as the size distribution shifted toward smaller floes and the number of floes increased. Dynamics breaks floes, decreasing the floe size and increasing the total floe perimeter and the number of floes. Associated with the increase in total floe perimeter is an increase in the total amount of lateral melting. Lateral melting decreases floe size and perimeter and may reduce the number of floes by eliminating smaller floes. As a result, lateral melting causes the distribution to deviate from a power law for small floe sizes.

Arntsen et al. [in press] investigates the summer evolution of floe size in the Beaufort Sea region by examining a sequence of National Technical Means imagery following a Lagrangian drifting buoy. This work verifies the insights of Perovich et al. [2001] and Perovich and Jones [2014], and further reveals the important role of melt ponds and ridges in determining the fate of the sea ice cover through the summer melt season. As melt accelerates, the floe breaking pattern, and therefore the floe size distribution, is heavily influenced by the distribution of melt ponds. As illustrated in Figure 1, the network of mature melt ponds acts as linked perforations facilitating summer floe breakup. A sea ice discrete element model [Hopkins et al., 2004], using morphological conditions derived from the analyzed satellite imagery, confirms that breaking occurs along ponds perpendicular to applied stress. Flooded subduction zones along ridges are another area where ice is likely to become heavily ponded, weaken, and break. These zones form during dynamic events in the winter and subsequently return to play an important role during summer breakup.

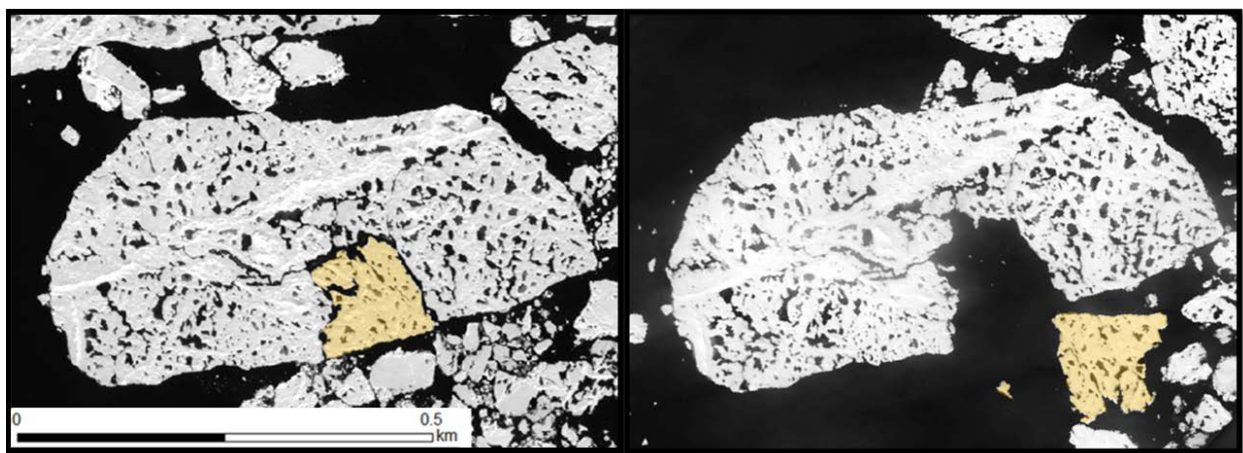


Figure 3. Before (30 July) and after (02 August) high resolution images of a floe breaking event, illustrating the process of preferential breakage along pond boundaries that have become linked.

IMPACT/APPLICATIONS

Previous studies have determined floe size distributions for different locations in both the Arctic and the Antarctic. Wave-ice interaction has been cited as a primary mechanism of floe break up in the traditionally defined MIZ, causing flexural failure and breaking of the ice cover. In the interior of the Arctic ice pack (e.g. Beaufort Sea) where waves are not prevalent, comprehensive programs like the ONR Marginal Ice Zone (MIZ) DRI are helping us understand that other processes govern the seasonal evolution of the MIZ. These processes are primarily driven by thermodynamics, and significantly influenced by key morphological features including refrozen crack and lead, subducted ice zones along ridges, and melt ponds.

Identifying the processes that govern the evolution of the floe size distribution is a key to understanding the evolution of the marginal ice zone that forms seasonally in the southern Beaufort and Chukchi Sea region. The floe size distribution directly impacts the partitioning of the solar radiation absorbed in the upper ocean. The absorbed sunlight contributes to warming the water, melting on the underside of the ice and melting at the lateral edges of the floes. The warming water and melting ice leads to a significant positive feedback, causing more open water, a thinner ice cover and

more solar energy absorbed. The improved understanding of the evolution of the floe size distribution will ultimately contribute to improvements in the ability to model the future condition of the sea ice cover on both the seasonal and decadal time scales.

The primary objective of our future work, building on the results of this project, is to establish a comprehensive floe breaking function. We will further develop and apply image processing techniques to identify and track the evolution of morphological features within the ice cover on scales from meters to 1 km. The output from the image processing workflow will be used to develop a quantified representation of the evolution of the ice cover, as a function of ice morphology and driven by dynamic and thermodynamic processes. Ultimately, this image processing technique can be applied to satellite images of the ice cover in late spring to predict the fate of the ice through the summer season.

Results from the current project have been and will continue to be used to both initialize and evaluate the CRREL sea ice discrete element model's (DEM) ability to simulate the observed evolution of the seasonal MIZ. We hypothesize that the DEM, a model designed to capture detailed ice interaction at the floe scale, is an effective tool for investigating the processes governing the floe size distribution and forecasting ice conditions. To test this hypothesis, we are making qualitative comparison of the model results against the time series of the satellite images used as part of this project. Image analysis from the project will provide a more detailed and quantitative comparison of the evolution of floe properties, to include floe size, area fraction and floe perimeter.

RELATED PROJECTS

- ONR Marginal Ice Zone Departmental Research Initiative:
<http://www.onr.navy.mil/en/Science-Technology/Departments/Code-32/All-Programs/Atmosphere-Research-322/Arctic-Global-Prediction/Marginal-Ice-Zone-DRI.aspx>

The goal of this five-year DRI, (FY12-FY16) is to improve the knowledge and understanding of the physics of the retreating summer ice edge and Marginal Ice Zone (MIZ) in the Beaufort and Chukchi seas. The approach will be to integrate data from *in situ* sensing platforms, remotely-sensed observations, and integrated process models to develop a comprehensive, quantitative picture of open-ocean, ice edge and MIZ processes, interactions and feedbacks as the ice retreats.

- CRREL: We coordinating with the following projects to obtain, process and apply satellite imagery to provide information about the initial configuration and condition of the ice cover for the DEM model and to evaluate the performance of the DEM in the modeling the evolution of the MIZ.
 - Song: “Evaluating the Discrete Element Method as a Tool for Predicting the Seasonal Evolution of the MIZ”, Office of Naval Research Grant # N0001414MP20126.
 - Polashenski: “Remote Sensing of Meter-Scale Sea Ice Properties”, Office of Naval Research Grant # N0001414WX20362.

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PUBLICATIONS

- Perovich, D.K. and K.F. Jones (2014) The seasonal evolution of sea ice floe size distribution, *J. Geophys. Res.*, 119, 8797-8777, doi:10.1002/2014JC010136. [published, refereed]
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